Brief Status Report on GSD Evaluation of Thompson-Eidhammer Aerosol-aware Microphysics in the Context of Other Physics Changes

(Aviation Weather Research Program, Model Development and Enhancement Product Development Team Deliverable 15.5.3.E3)

John M. Brown, Joseph B. Olson, Jaymes Kenyon, and others on the RAP / HRRR Development Team

September 2015, revised 4 October 2015

1. Background and goal

The traditional categorization of physics schemes in numerical models

- Long wave radiation (absorbed and reemitted by the air, clouds and the ground)
- Short (incoming and reflected solar) wave radiation
- Land-Surface process Model (LSM)
- Atmospheric surface layer and planetary boundary layer (PBL)
- Cumulus convection
- Cloud and precipitation microphysics,

is convenient, but somewhat arbitrary; nature doesn't necessarily recognize our distinctions. So, the interaction between schemes needs to be well designed in the context of natural processes, and the relative importance of often multiple aspects of these interactions well represented.

Here we describe the status of our assessment of the impact of other physics changes on the behavior of the Thompson-Eidhammer (2014) microphysics. This assessment remains a bit sketchy at this point. More extensive testing using parallel real time cycles as well as longer retrospective periods will be conducted in coming months.

Owing to the delay in the RAPv3 / HRRRv2 implementation, now scheduled for 23 February 2016, it appears unlikely that NCEP will be able to accept new code for RAPv4 / HRRRv3 until later in 2016, giving a few months additional time for further physics development before the RAPv4 / HRRRv3 code must be frozen for transfer to NCEP. The main thrust of this development, which is partially supported by other agency funding, is toward a more unified approach to the representation of boundary-layer processes and low-altitude clouds that are closely coupled to these processes. The aerosol-aware microphysics is obviously highly relevant here.

There is at present a substantial effort involving investigators from several countries toward better understanding of processes contributing to vertical energy transport in the form of heat and moisture between the ground surface and the atmosphere. These processes include fluxes between the atmosphere and the surface, turbulent fluxes in the lower atmosphere that may be shear-generated or in the form of buoyant plumes rising from the surface, condensation to form clouds in local areas of ascent, and attenuation of solar radiation by clouds so generated, with consequent feedback effects. Accurate representation of these processes in models touches all the categories of physics schemes noted above (including the Thompson-Eidhammer aerosol-aware microphysics in the RAP and HRRR.

The goal of this work in GSD is to arrive at, over the next several months, a physically based parameterization that effectively couples subgrid-scale processes in the boundary layer to formation, maintenance and dissipation of clouds that result from these processes. To be successful, this parameterization must provide a quantitatively accurate impact of these subgrid processes on the explicitly predicted flow. Our work thus has direct relevance to prediction of aviation impact variables such as ceiling, visibility, winds, wind shears and turbulence at low levels (say in the lowest 1 to 2km of the atmosphere), as well as icing within low-level clouds. It is therefore relevant to several subtasks under MDE task 3. In what follows, we present some comparison of forecast results with the new aerosol-aware microphysics and with the Thompson aerosol unaware microphysics currently operational at NCEP in both the RAP and HRRR. We then briefly discuss 3 components of our ongoing development that are of direct relevance to the near and medium term configuration of RAP and HRRR.

2. Comparison of aerosol-aware and unaware Thompson microphysics

A HRRR comparison was made recently of the performance of the WRFv3.6.0 version of the Thompson-Eidhammer microphysics (hereafter MP28, referring to namelist option in WRF) relative to the Thompson unaware microphysics (hereafter MP8) based on Thompson et al 2008. The only difference between the runs was the version of the microphysics. This retrospective experiment in mid-July 2014, was only for 3 d, but we believe demonstrates qualitatively the differences in forecasts of convection produced by the schemes.

Figure 1 shows Critical Success Index (top 4 graphs; larger values better) for diagnosed composite radar reflectivity exceeding 15, 25, 35 and 45 dbZ over 20km X 20km averaging areas (reflectivity Z is the quantity actually averaged) and bias (bottom 4 graphs) on the native HRRR grid (ratio of number of 20-km X 20km averaging areas having forecast reflectivity exceeding 15, 25, 35 and 45 dbZ to the number observed; zero bias corresponds to a value of one) for the retrospective period[1]. This is for an area covering approximately the eastern half of the CONUS where radar coverage is fairly complete. It is seen that CSI results for the two schemes are very similar overall, but with MP8 having a slight

---

[1] These reflectivities are computed directly from the forecast hydrometeor

advantage after the first few hours. Because of the small sample size, CSI for the 45 dbZ threshold is quite noisy and is not considered reliable.

Bias for MP28, on the other hand, is systematically smaller (and generally closer to one) for the weaker reflectivity thresholds, but very similar for 45 dbZ, suggesting little difference in the occurrence of intense cores of reflectivity, and less coverage by weaker reflectivity.

Figure 2 gives two examples of composite-reflectivity forecasts during the same July 2014 retrospective experiment. The 12-h forecast initialized at 09 UTC 17 July features a mesoscale convective system (MCS) covering much of eastern OK, east TX, and much of AR, with both convective and more stratiform areas of weaker reflectivity apparent. The forecasts are very similar, with discernable correspondence between even fairly small groups of cells in the two forecasts, both in the vicinity of the MCS and off the US east coast. The 6-h forecast initialized at 00 UTC 18 July, shows the MCS having moved east, but still persisting in both runs. These forecasts are also very similar, with some evidence for smaller coverage by echoes in the 30-40 dbZ range in the MCS for the aerosol-aware run, perhaps a manifestation of the smaller bias for reflectivity thresholds noted in Fig. 1.

Further analysis of these runs is underway to better understand these reflectivity differences. One hypothesis is that the climatological water-friendly aerosol distribution used in MP28 with it's 2-moment (cloud water mixing ratio and number concentration of cloud drops both predicted) is producing a larger number of smaller cloud drops in areas of condensation over land areas than is MP8, which specifies a spatially invariant distribution of cloud-drop sizes given a certain mixing ratio of cloud water. The MP8 cloud-drop distribution is suspected of containing a wider size range than that of MP28 over land, reducing the efficiency of collision-coalescence production of rain (the so-called warm-rain process) over that in MP8 over land areas. This smaller rain production would account for lower reflectivities, but also make for thicker, more persistent clouds. This and other possibilities are under investigation.

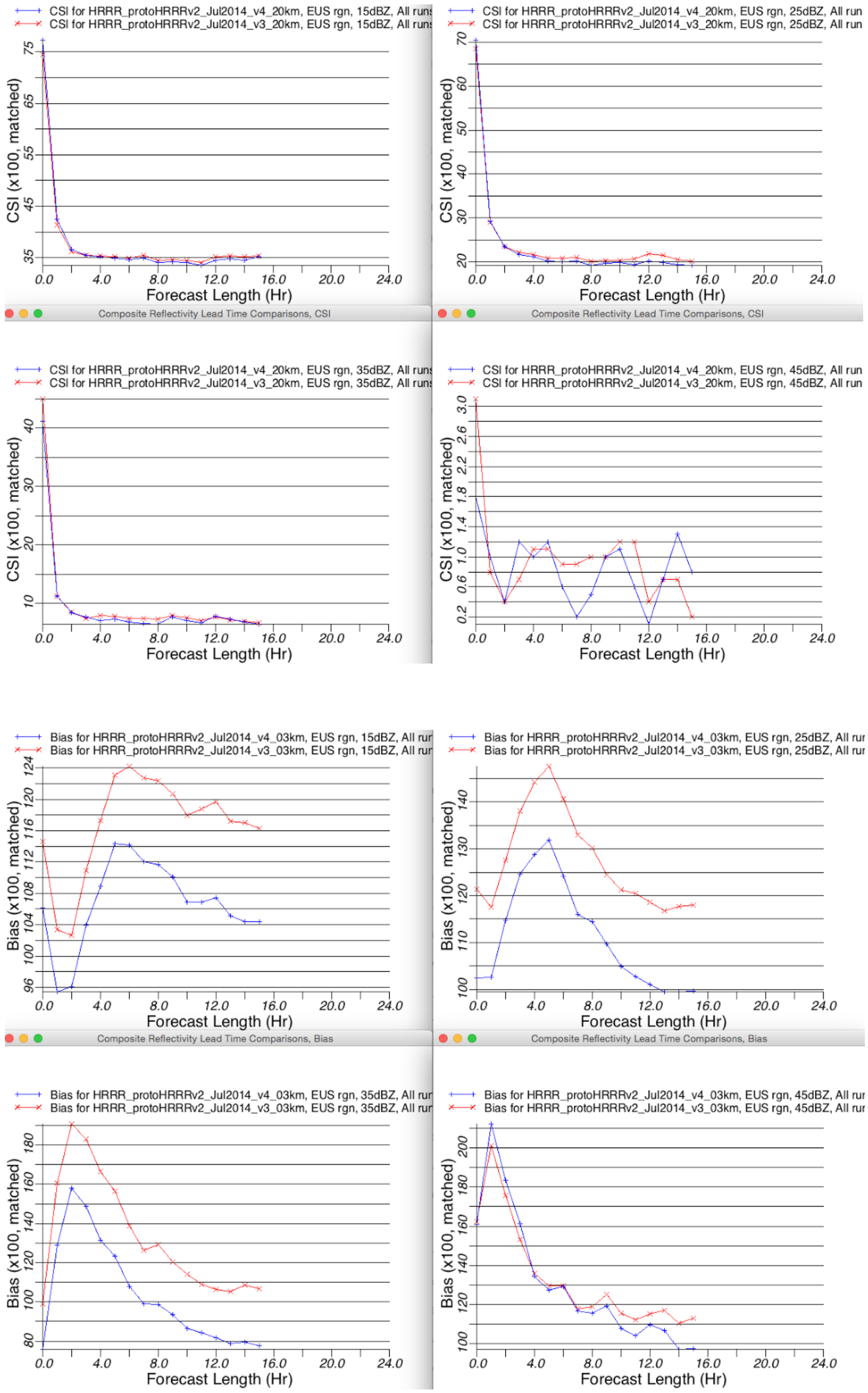
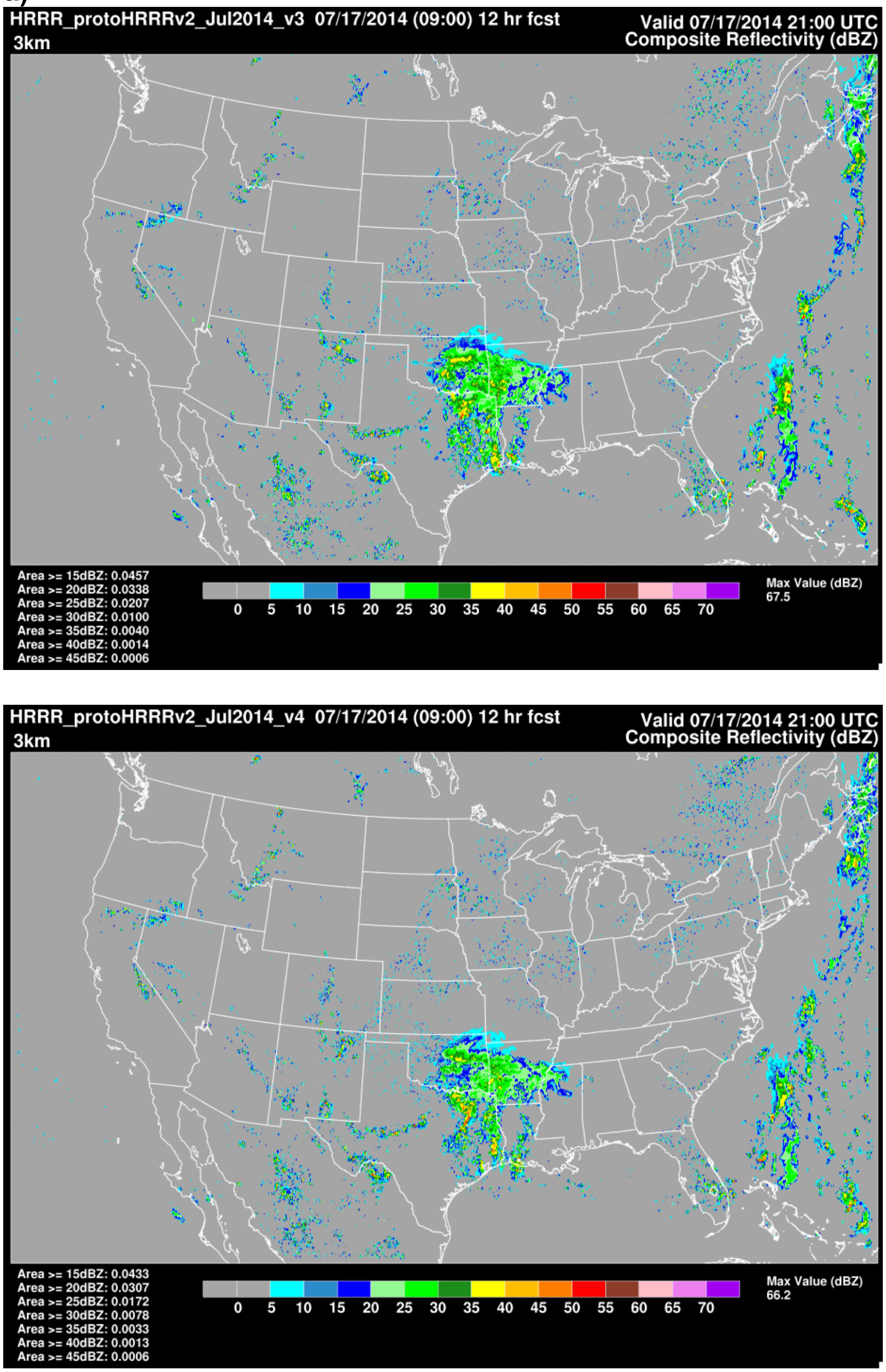


Figure 1. Results from HRRR short retrospective experiment comparing Critical Success Index (CSI, top 4 panels) and bias (bottom 4 panels) for composite reflectivity for runs using MP8 (red curves) and MP28 (blue curves). See text.

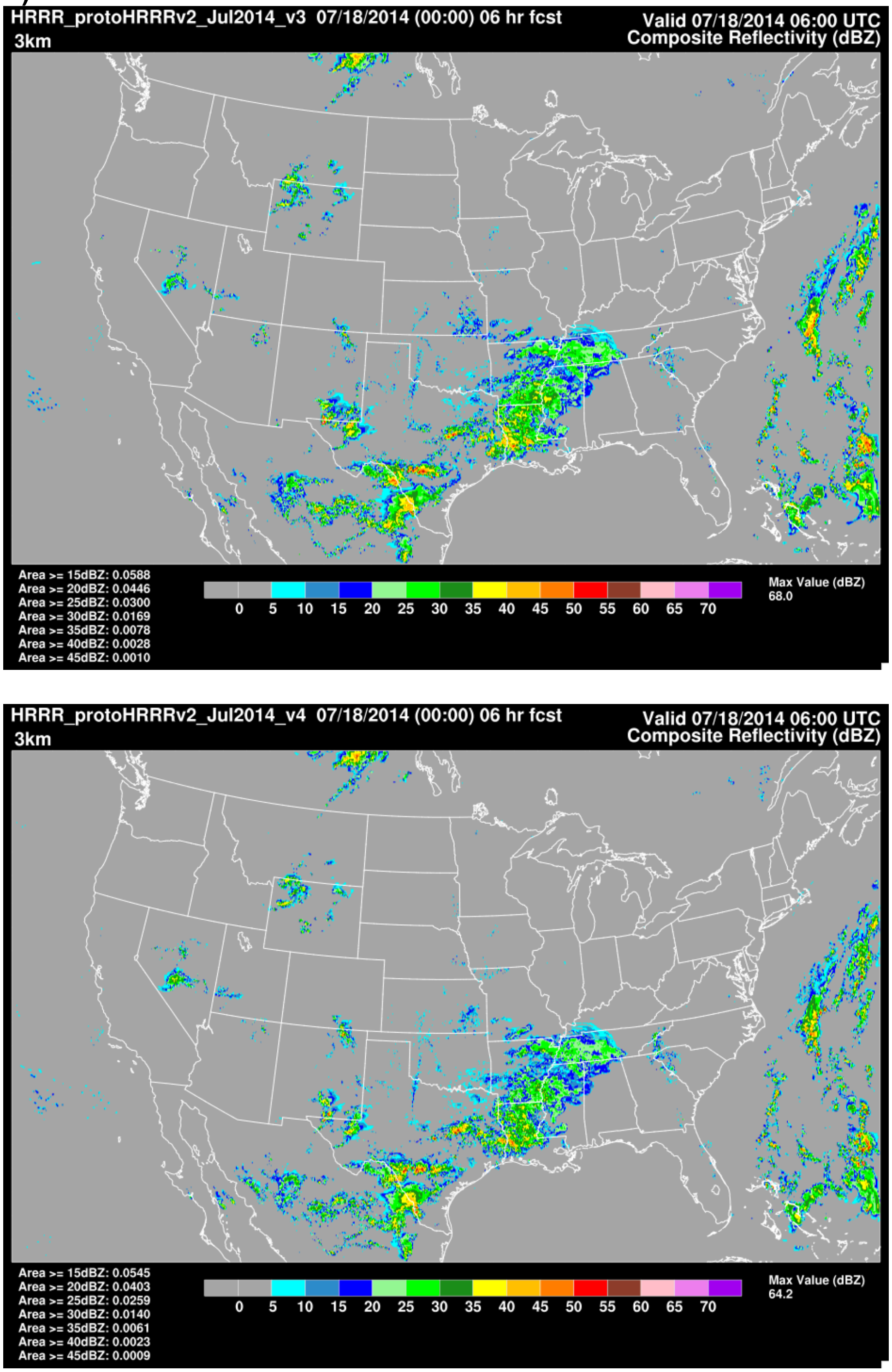
a)



Aerosol unaware

Aerosol aware

b)



Aerosol unaware

Aerosol aware

Figure 2. Two examples of composite reflectivity forecasts from MP8 and MP28. a) 12h forecasts initialized 09z 17 July 2014. Top panel is from MP8 and bottom panel is from MP28. b) As a) except 6-h forecasts initialized 00z 18 July 2014.

3. GSD physics development activities relevant to MP28 performance

1) Background. At present, stratiform and cirriform clouds in the operational RAPv2 and HRRRv1 are represented solely by the microphysics scheme. The current design of this scheme (and other microphysics schemes in WRF) requires a grid cell to have a relative humidity of 100% to contain cloud. Consequently, only those stratiform and cirriform clouds that are sufficiently extensive to produce grid-scale saturation are represented. Stratus and cirrus layers of modest vertical or horizontal extent (i.e., subgrid scale) will fail to produce grid-scale saturation and therefore go unrepresented in the RAP and HRRR. The cool-season high bias in RAP GHI[2] forecasts (Fig. 3, top panel, positive values indicate too much solar radiation reaching the surface) may be attributed, at least in part, to this non-representation of subgrid-scale stratiform and cirriform clouds in the RAP.

The RAPv3 indicates much improved prediction of GHI over that of the operational RAP, particularly during late spring of 2015. Part of this improvement is attributable to the Thompson-Eidhammer (MP28) aerosol-aware microphysics, but the greater portion we think, based on subjective evaluation (we have not performed the retrospective experiments necessary to quantify this), is achieved by accounting for the attenuation of incoming solar radiation by the parameterized boundary-layer cloudiness (primarily shallow Cumulus or Stratocumulus in nature) in the MYNN pbl scheme, an enhancement that was introduced in 2014 and made part of RAPv3 / HRRRv2 that will be implemented early in 2016.

However earlier in the year (Fig. 3), *both* the operational RAPv2 and the new RAPv3 show a small but systematic high bias in incoming solar radiation. Examples of this problem in winter are illustrated in Fig. 1, bottom panels. The lower-left panel shows very low Stratus over the Central Valley of California that was not well predicted by the model (solar irradiance forecast much too large through morning and midday). The lower right image shows thin Cirrus over New Mexico that reduced insolation somewhat more than indicated by the model forecast.

[2] Global horizontal irradiance, a measure of the short-wave radiation from the sun reaching a horizontal surface on the ground.

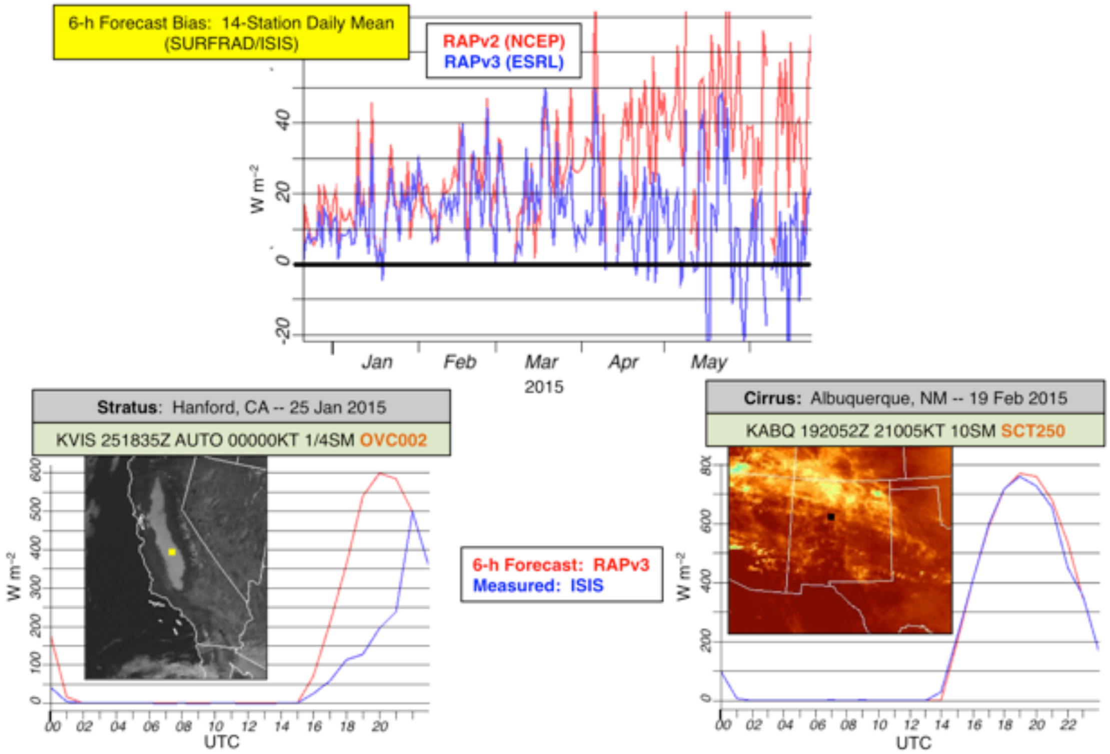


Figure 3. Top panel: Comparison of forecasts of GHI by the operational RAPv2 at NCEP (red curve) with the RAPv3 forecasts with improved partial cloudiness representation. Positive values indicate GHI greater than measured by the 14 NOAA SURFRAD and ISIS stations scattered about the CONUS. Bottom panels: Two examples of excessive GHI predicted by the RAPv3 in winter. Left panel is for low Stratus in California's Central Valley—the model failed to adequately capture this thin low-cloud deck. Right panel shows a less severe example, in this case failure to adequately predict attenuation by thin Cirrus.

2) Representation of subgrid-scale clouds We are exploring ways to represent subgrid-scale stratus, stratocumulus, altocumulus and cirrus via statistical cloud schemes. The WRF microphysics schemes as presently formulated do not allow clouds [represented as >0 mixing ratio (qc) of liquid drops or of ice crystals (qi) in the Thompson-Eidhammer microphysics scheme] to be present in a grid volume unless that grid volume is predicted to have a relative humidity of 100% with respect to water at temperatures ≥ 0C, and at least 100% ice saturation at colder temperatures. However, Cumulus, Stratocumulus, Altocumulus and often Cirrus clouds are typically smaller than a grid volume in the 13km RAP, and often smaller than that of a grid volume in the 3km RAP. To evade this conundrum, statistical cloud schemes have been designed that can represent clouds, or more

precisely, a fractional coverage by clouds, in subsaturated grid volumes. And unlike shallow-cumulus convective-parameterization schemes, statistical cloud schemes are intended to represent all cloud genera. The Chaboureau and Bechtold (2002, hearafter C-B) statistical cloud scheme is a candidate parameterization under testing in RAP / HRRR. Preliminary results indicate that this scheme is better able to produce small and intermediate cloud fractions than the Sommeria and Deardorff (1977) scheme currently in use (Fig. 2).

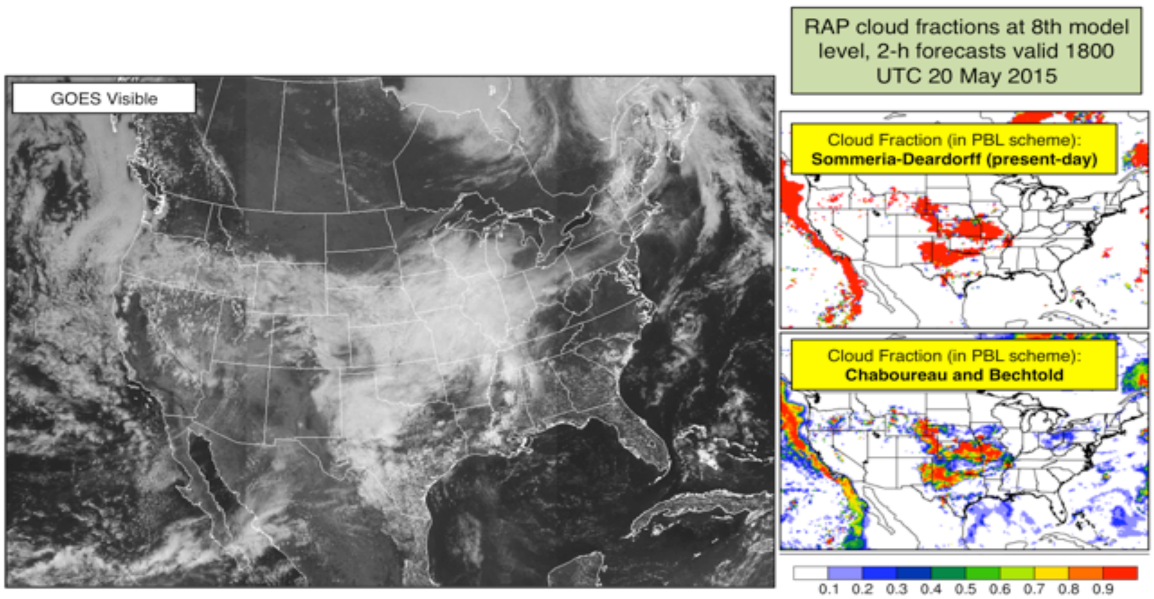


Figure 4. Left: GOES visible image for 1800 UTC 20 May 2015. Right: Forecast RAP cloud fraction (scale at bottom) using the Sommeria-Deardorff (top) and Chaboureau and Bechtold (bottom) formulations.

Importantly, the Chaboureau and Bechtold (2002, hereafter C-B) scheme, by better accounting for subgrid-scale stratiform cloudiness (Stratus, Stratocumulus, Altocumulus, Altostratus) by use of non-Gaussian joint probability distribution functions is capable of adding additional depth and horizontal coverage to modeled stratus layers (Fig. 5). We hypothesize that this subgrid-scale stratus, implemented with full radiative coupling, will facilitate more accurate RAP and HRRR forecasts of the timing and duration of stratiform clouds, which contribute overwhelmingly to instances of low ceilings. Now that RAP and HRRR development cycles have been set up on the new Theia supercomputer, it will be possible to more rigorously test the viability of the C-B scheme.

Both the C-B and Sommeria - Deardorff schemes have been coupled to the RRTMG long- and short-wave radiation schemes using simple assumptions regarding the microphysical properties of the clouds. In principle these assumptions should be consistent in some sense with the cloud properties that would be produced by the aerosol-aware microphysics were explicit clouds being forecast. A possible approach here is to combine the Chaboureau – Bechtold fractional cloudiness scheme with the Thompson-Eidhammer microphysics by partitioning grid cells into clear and cloudy portions, with the cloud fraction being determined by the C-B scheme and the microphysical processes within the cloudy portion being described by the Thompson-Eidhammer microphysics. Further, the implied latent heat release or absorption from time changes in the parameterized fractional cloudiness from time step to time step needs to be accounted for, rather than being neglected as at present. Obviously, to improve consistency here more work is needed.

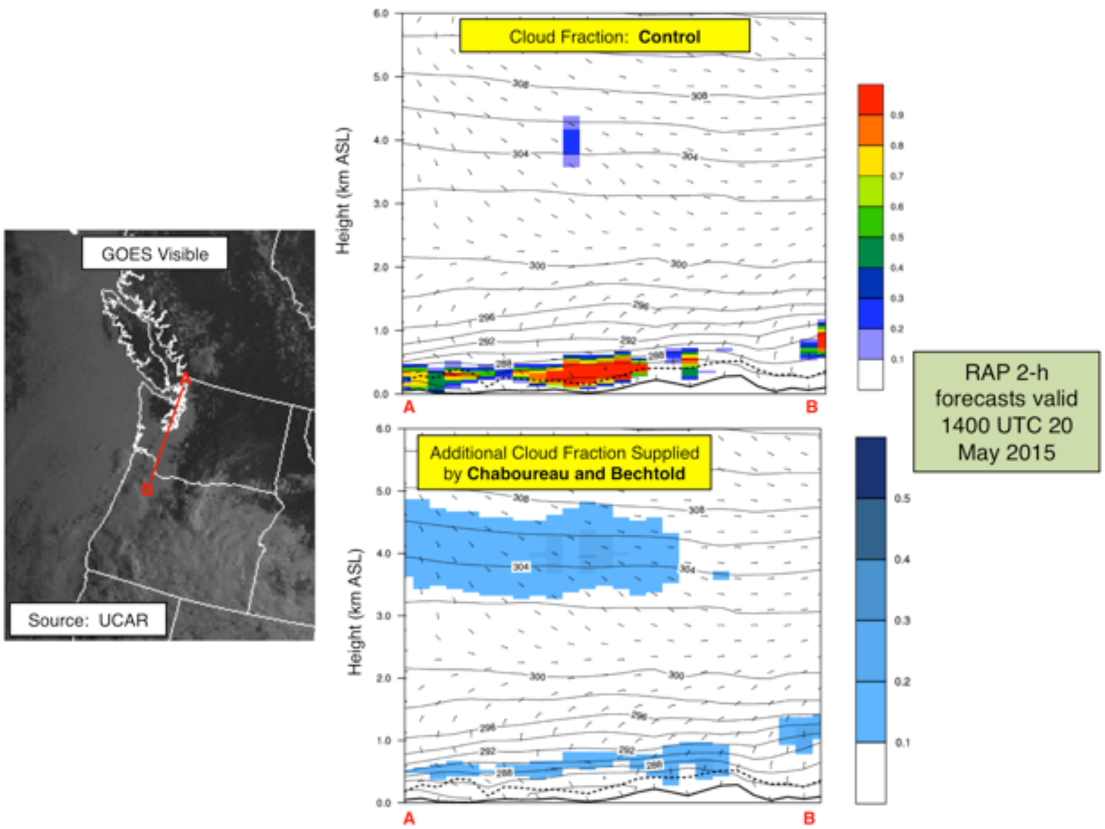


Figure 5. Left: visible satellite image for 1400UTC 20 May 2015, showing extensive low clouds over WA and OR west of the Cascades. There is considerable middle and high cloudiness over much of OR also. Right: North-south vertical section of RAP 2-h forecast valid for time of satellite image. Location of cross-section is shown on left image, and is mostly east of the coastal mountains and west of the Cascades. Top: cloud fraction produced by the Sommeria-Deardorff scheme currently in use. Bottom: *Additional* cloud fraction produced when the Chaboureau-Bechtold scheme is used. Note that fractional coverage by both marine-layer cloudiness and middle-level Altocumulus are augmented.

3) Major enhancement to the MYNN PBL scheme. The MYNN scheme is a local-mixing scheme based on the Mellor-Yamada (1982) formulation of the boundary-layer turbulent transports. As such, it is not designed to describe processes in the unstable boundary layer over land with strong surface heating, in which the majority of the vertical turbulent heat transport is accomplished by buoyant thermals originating near the surface and rising to the top of the mixed layer. In recent years a so-called “eddy diffusivity – mass flux” (EDMF) approach

has arisen to account for this deficiency. An essential aspect of this approach is that it allows for countergradient heat transport within the mixed layer in the sense that buoyant thermals transport heat upward even though the mixed layer itself in the mean has slight stratification above the unstable surface layer where the buoyant thermals originate. Here, under conditions of strong surface heat flux, the local mixing of the Mellor-Yamada formulation is supplemented (or replaced) by a representation of eddy vertical transport of momentum, moisture and heat by buoyant thermals.

Joe Olson is currently coding this mod into a recent version of the MYNN code.

<u>4) Ceiling algorithm improvement.</u> Lastly, the emerging capability of representing subgrid stratus clouds presents an opportunity to improve the ceiling algorithm used during RAP / HRRR postprocessing using the NCEP UniPost code. In the present-day form, ceilings are diagnosed from resolved-scale cloud-condensate mixing ratio and boundary-layer-top relative humidity. With the expected availability of subgrid-scale stratus information, a simplified cloud-ceiling algorithm is in development, which uses cloud fraction as its sole predictor. Following convention, if there are several layers of clouds, the height AGL of the lowest cloud layer for which the sky coverage of the union of that layer and any layers below is > 50% defines the ceiling. Preliminary tests indicate superior skill of this algorithm (via the true skill statistic, TSS) over the present-day approach (Fig. 6). Further evaluation of this algorithm using parallel cycles and retrospective testing in RAP and HRRR to cover all seasons will be necessary to see if these dramatic improvements hold up in a wide range of situations.

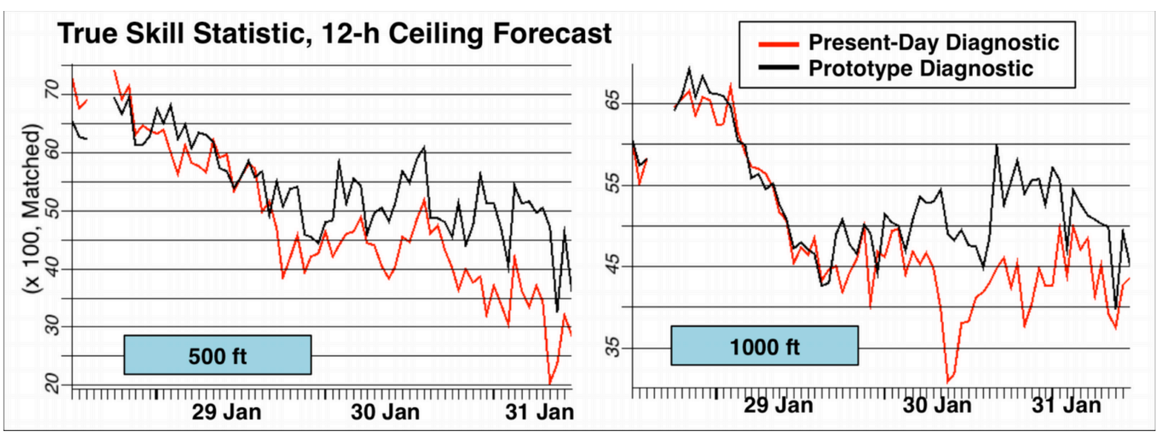


Figure 6. True Skill statistic for 12-h ceiling forecasts of < 500ft and < 1000ft ceilings. Results from the current procedure

4. Challenges and future work

The following are activities that will be necessary to bring the work summarized in section 3 to the point where it can be included in RAPv4 / HRRRv3 and subsequent model upgrades.

- Testing and evaluation of the C-B partial cloudiness scheme and its impact on the Thompson-Eidhammer microphysics and other physics using real time and retrospective experiments. Some "tuning" of parameters in the C-B scheme (particularly the mixing length—can the MYNN's master length scale be used?) may be necessary. Also, whether a partial-cloudiness scheme is necessary in the higher-resolution 3-km grid spacing HRRR, in which a wider size-range of clouds can be explicitly resolved, needs to be investigated.

- Comparison with Thompson RH-based partial cloudiness scheme (MDE subtask 15.3.x.y).

- Ensuring consistency of properties of clouds implied by partial cloudiness schemes with Thompson-Eidhammer microphysics, including thermodynamical effects of implied condensation, evaporation, etc., as cloud fraction changes.

- Testing of new EDMF version of MYNN and ensuring consistency with formulations of partial cloudiness and parameterization (if any) of shallow convection

5. References

Chaboureau, J.-P., and P. Bechtold, 2002: A simple cloud parameterization derived from cloud-resolving model data: diagnostic and prognostic applications. *J. Atmos. Sci.*, **59**, 2362-2372.

Sommeria, G., and J. W. Deardorff, 1977: Subgrid-scale condensation in models of non-precipitating clouds. *J. Atmos. Sci.*, **34**, 344-355.

Thompson, Gregory, Paul R. Field, Roy M. Rasmussen, and William D. Hall, 2008: Explicit Forecasts of Winter Precipitation Using an Improved Bulk Microphysics Scheme. Part II: Implementation of a New Snow Parameterization. *Mon. Wea. Rev.*, **136**, 5095–5115. doi: http://dx.doi.org/10.1175/2008MWR2387.1

Thompson, G., and T. Eidhammer, 2014: A Study of Aerosol Impacts on Clouds and Precipitation Development in a Large Winter Cyclone. *J. Atmos. Sci.*, **71**, 3636-3658.